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Isolated Effect of pH on The Rheological, Filtration, and Lubricity Characteristics of Polymer-Free Bentonite Drilling Fluids

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ABSTRACT - Alkalinity is a key control parameter in water-based drilling muds (WBM), yet its intrinsic influence on bentonite systems independent of specialty additives remains poorly resolved. This study examines the effect of pH variation on the rheological, filtration, lubricity, and flow-modeling behavior of bentonite-based WBMs formulated at pH 7.5 (control), 8, 10, and 12 using potassium hydroxide as the pH modifier. All measurements were conducted in accordance with API RP 13B-1 standards. Results show that increasing alkalinity progressively disrupts mud structure, with plastic viscosity and yield point declining by approximately 50–67% between pH 7.5 and 12. Rheological modeling using Bingham Plastic, Power Law, and Herschel–Bulkley formulations confirms this trend, as yield stress parameters and model fidelity deteriorate at elevated pH, particularly at pH 12. Extreme alkalinity also adversely affected filtration behavior, increasing API fluid loss from 22.0 to 77.7 mL and producing thicker, more permeable filter cakes. In contrast, lubricity showed a modest improvement with increasing pH, with the lubricity coefficient decreasing from 0.49 to 0.43. The results highlight a clear performance trade-off, indicating that excessive alkalinity undermines rheological stability and fluid-loss control despite minor gains in lubricity, thereby supporting the use of moderate alkalinity for balanced WBM performance.

Keywords: alkalinity control, bentonite dispersion, filtration, lubricity, rheology, viscosity

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INTRODUCTION

Drilling fluids, commonly known as drilling muds, are complex heterogeneous systems composed of liquids, solids, and chemical additives, and have remained essential to oil and gas well construction since the early 1900s (Rasool et al., 2024). Based on their base medium, drilling fluids are classified as pneumatic fluids (air and natural gas), liquid-based systems (water-based and oil-based muds), and pneumatic–liquid mixtures such as foams and aerated fluids. Although their initial role was limited to cuttings transport, advances in drilling engineering have expanded their functions to include wellbore stabilization, pressure control, formation protection, equipment preservation, and overall drilling efficiency (Moore, 1974; Rasool et al., 2024; Deville, 2022).

The success of rotary drilling operations depends strongly on drilling mud performance, particularly its rheological properties (Mohamed et al., 2021; Liu et al., 2021; Aliu et al., 2025). Parameters such as plastic viscosity (PV), yield point (YP), and gel strength govern cuttings transport, suspension during static conditions, and hydraulic efficiency during circulation.

It is critical to control and maintain rheological properties as a failure to do so can result in financial and loss of time, and in extreme cases, it could result in the abandonment of the well, particularly where excessive fluid invasion alters reservoir pressure support and water influx behavior (Aliu et al., 2025b). Effective drilling fluid selection therefore requires an understanding of formation type, temperature range, formation strength, permeability, pore pressure conditions, and pore fluid characteristics of the formation, especially in heavy hydrocarbon systems where fluid–rock interactions are highly sensitive to drilling-fluid chemistry (Ahmed & Kalkan 2019; Akinsete et al., 2025).

Rheology, defined as the study of deformation and flow of matter, underpins the analysis of drilling fluid behavior under both static and dynamic conditions (Morrison 2001). In drilling applications, rheological properties influence velocity profiles, frictional pressure losses, annular cuttings transport, and overall wellbore hydraulics (Mahmud et al., 2026; Stanciu, 2024). Poor rheological control can lead to excessive pressure losses, inefficient hole cleaning, stuck pipe, and, in severe cases, well abandonment (Darley & Gray, 1988; Ogolo et al., 2021). As a result, rheological testing is routinely performed alongside filtration tests, pH monitoring, alkalinity and lime content determination, ionic composition analysis, and resistivity measurements during drilling operations. To meet varying downhole conditions, drilling fluids are modified using chemical additives such as viscosifiers, weighting agents, fluid-loss reducers, emulsifiers, flocculants, corrosion inhibitors, defoamers, and pH control agents (Suhascaryo & Dhaffa, 2024; Akinsete & Aliu, 2023). Among these, pH control is particularly important because alkalinity directly influences clay hydration, surface charge, interparticle interactions, and the performance of other additives in water-based muds (Huang et al., 2019; Oliveira et al., 2018). Table 1 shows a summary of studies on the effect of pH on the different properties of drilling mud.

Changes in drilling fluid pH during operations often indicate contamination by gypsum, carbon dioxide, or acidic formation fluids, requiring corrective treatment to restore mud performance (Samura et al., 2025). Reductions in pH have been attributed to water contamination, carbonate and bicarbonate intrusion, and acidic gases such as carbon dioxide and sulphur dioxide (Hong, 2017; Peretomode, 2021; Caenn et al., 2011). In addition, pH significantly affects corrosion behavior, as mud chemistry, flow rate, and temperature collectively influence drill pipe and downhole equipment degradation (Yahya et al., 2022; Chen et al., 2024; Mahamadou et al., 2024; Permana et al., 2025). Consequently, field practice typically maintains water-based muds within a mildly alkaline range of approximately pH 9.5–10.5, with higher alkalinity applied when hydrogen sulphide (H_2S) is anticipated (Baker Hughes, 2006; Carvalho, 2023; Retnanto et al., 2024; Permana et al., 2025).

Previous studies have documented that increasing alkalinity generally weakens bentonite-based mud rheology and increases fluid loss by promoting platelet dispersion and reducing interparticle attraction (Gamal et al., 2019;

Rafieefar et al., 2021). However, most investigations focus on additive-rich systems or polymer-modified formulations (Table 1), making it difficult to isolate the intrinsic effect of pH on bentonite behavior. Moreover, the influence of alkalinity on lubricity particularly in the absence of dedicated lubricating additives has received comparatively limited attention, despite its operational importance. Lubricity is a key property affecting torque, drag, and mechanical wear, particularly in directional and extended-reach drilling operations (Fadairo et al., 2019; Fadairo et al., 2021).

This study addresses these gaps by systematically examining the isolated effect of pH on the rheological, filtration, and lubricity properties of a bentonite-based WBM formulated without polymers, fluid-loss agents, or specialty additives. By evaluating mud performance across a broad alkaline range (pH 7.5–12), the work provides a clear mechanistic understanding of how alkalinity alone modulates clay dispersion, flow resistance, filter-cake development, and frictional behavior. The findings offer practical guidance for optimizing pH control in water-based drilling fluids, balancing rheological strength, filtration performance, and lubricity for efficient and environmentally responsible drilling operations.

METHODOLOGY

Materials

Fresh water, bentonite, and caustic potash were the materials used. The materials were of analytical grade and supplied by the laboratory of the department of Petroleum engineering, University of Ibadan were the experiment was carried out.

The pH was measured using Jenway 3520 pH meter, the Fan 35A rheometer was used to obtain measurements for determining the rheological properties of the mud, the Ofite filter press (Model 140-50) was used for the filtration properties, while the Ofite lubricity Tester (Model 112-00) was used to measure the torques reading for the lubricity coefficients.

Methods

The base fluid for the drilling mud formulation was fresh water, while bentonite served as the primary viscosifier. Caustic potash (KOH pellets) was used to adjust alkalinity and create mud systems at target pH values of 8, 10, and 12, alongside a control mud maintained at natural pH. Each mud sample was prepared at a standard composition of 350 mL water and 21.5 g bentonite, with KOH concentration varied to achieve the desired alkalinity levels (Table 2). The bentonite suspensions were prepared following the API RP 13B-1 recommended practice with modifications for the study objectives (API, 2017).

The drilling mud samples were prepared by first creating alkaline base fluids. Forty grams of potassium hydroxide (KOH) pellets were dissolved in measured volumes of distilled water and stirred continuously until full dissolution and a clear, homogeneous solution was obtained. The pH of each solution was then measured using a calibrated digital pH meter. Additional KOH was added gradually to the other three samples, with continuous stirring, until the desired pH values of 8, 10, and 12 were achieved. Distilled water at its natural pH was retained as the control sample. From each prepared solution, a fixed volume of 350 ml was measured and transferred into separate API multimixer cups.

For mud formulation, 21.5 g of bentonite was accurately weighed for each sample using a calibrated electronic balance. With the multimixer in operation, the bentonite was slowly added into the respective cups containing the base fluids. The solids were introduced gradually using a spatula to prevent agglomeration and to promote uniform dispersion within the fluid. Mixing was continued under controlled conditions for approximately 10 minutes until a smooth, homogeneous, and lump-free drilling mud was obtained. Upon completion of mixing, the multimixer cups were removed and the prepared mud samples were considered ready for evaluation. The fresh samples were immediately subjected to rheological, filtration, and lubricity measurements in accordance with standard testing procedures, ensuring minimal aging effects prior to testing. Conventional

Table 1. Summary of reported effects of pH on rheological, filtration, and lubricity properties of bentonite-based water-based drilling muds.

Reference	Material / additive	Reported concentration (as stated)	Mud type	Observed effect (rheology / filtration / lubricity)	Key note / implication
Huang et al. (2016)	API bentonite	7 wt%	Clay suspensions (analogous to WBM)	Zeta potential and yield stress change with pH; below the point-of-zero-charge (PZC) interactions increase (thicker gels), above PZC they weaken.	Shows pH shifts surface charge causing changes to aggregation/ dispersion and therefore rheology.
Li et al. (2018)	Bentonite (BT) + chitin and Chitin nanocrystals (ChNCs)) and PAC	3 wt % BT + 0.1 wt % chitin and ChNC suspension	WBM with pH-responsive components	Demonstrated pH-responsive control of viscosity/plugging — viscosity increased/decreased when pH changed, enabling tunable filtration/rheology.	pH-responsive polymers (bt + ChNCs) offer an active route to tune mud properties downhole (smart fluids).
Gamal et al. (2019)	Bentonite, NaOH, lignosulphate, and starch	pH varied 8– 12	Water-based mud (bentonite)	Increasing pH from ~8 to 12 decreased plastic viscosity by ~53% and yield point by ~82; filtration increased at high pH.	Shows strong sensitivity of bentonite rheology to pH — high-alkaline muds become much weaker and may give higher fluid los s.
Mohamed et al. (2020)	Perlite particles	0–3 lb/bbl	Water-based mud	Perlite slightly reduced pH with increasing concentration; rheology/filtration changes were observed but pH stayed within workable range in study.	Some solid additives can shift pH indirectly and recommend to check pH after adding solids.
Rafieefar et al. (2021)	Bentonite + Graphene oxide, Xanthan gum, and low-viscosity CMC	0.0 – 0.3% w/w	Water-based drilling fluids	Rheology and fluid-loss strongly depend on additive concentration and pH / ionic conditions; pH alters particle interactions and gel structure.	Highlights combined role of pH and ionic strength; recommends pH control during formulation/testing.
Perumalsamy et al. (2021)	Graphene nanoparticles + ester lubricants (PC60)	1, 2, and 3% by volume	Water-based mud (lubricity focus)	Graphene + esters improved lubricity and helped maintain rheology, but dispersion and performance were sensitive to pH and salinity.	Nanoparticles can boost lubricity and rheological stability but must be dispersed under controlled pH/salinity.
Qin et al. (2021)	Polyaspartate (PA) + Polyethylene glycol (PEG)	PA (0– 20 wt%) and PEG (0 – 7 wt%)	Water-based mud (lubricity additives)	PA+PEG improved lubricity while being more compatible with water-based systems; performance varies with pH (adsorption onto surfaces changes).	Biopolyme blends are promising water-based lubricants but require pH awareness for surface adsorption and friction reduction.

Table 1. Summary of reported effects of pH on rheological, filtration, and lubricity properties of bentonite-based water-based drilling muds. (continued)

Koo et al. (2022)	bleached nanofibrillated cellulose (NFC) and lignin-containing NFC (LNFC - from southern pine bark and tobacco leaf stem), and water-soluble polymers (WSPs – PAC and XG)	3.0 wt % BT, 0.5 wt % (L)NFC, and PAC/XG (0.0, 0.1, and 0.2 wt %)	Bentonite suspensions / WBM analogues	Additions (e.g., stabilizing agents) changed filtration and rheology; pH influenced gel microstructure and filter-cake behavior.	Confirms microstructure macro-propert pH control ess to manage flui and cake quali
Ali et al. (2022)	Natural waste (cupressus cones powder)	1–7 ppb	Water-based mud (additive study)	Additive changed rheology and filtration; pH was monitored — performance depends on both concentration and pH.	Checking of p interactions is necessary whe screening nov materials.

polymeric rheology modifiers like carboxymethyl cellulose (CMC) and polyanionic cellulose (PAC) were excluded because including them in a study focused on isolating the effects of pH on bentonite's intrinsic rheology would confound the interpretation of results. Since CMC and PAC directly contribute additional thickening and structural interactions independent of the clay's behavior (Safi et al., 2016), their presence could mask the true influence of pH on bentonite particle dispersion, colloidal interactions, and shear response. Potassium hydroxide (KOH) was used as the alkalinity control agent because it is commonly applied in water-based drilling fluids to increase pH and maintain chemical stability. The investigated pH range (7.5–12) was selected to encompass both near-neutral conditions and alkalinity levels that exceed the typical operational range of water-based drilling muds. In field applications, drilling fluids are generally maintained between pH 9.5 and 10.5 to promote clay hydration, minimize corrosion, and ensure compatibility with chemical additives. Extending the experimental range beyond this window allowed the study to evaluate how progressively increasing alkalinity influences bentonite dispersion and mud performance, including scenarios where excessive alkaline treatment or contamination may drive pH to unusually high values. Approximately 40 g of KOH was added to achieve the highest pH level investigated, enabling the systematic assessment of alkalinity effects while keeping the mud composition otherwise unchanged.

Measurement of rheology, filtration and lubricity properties

Rheological properties measured included plastic viscosity (PV), apparent viscosity (AV), yield point (YP), low-shear yield point (LSYP), shear stress, and dynamic viscosity. Filtration performance was evaluated through API fluid loss and filter cake thickness measurements. Lubricity was assessed by determining the lubricity coefficient using a lubricity meter, calibrated against fresh water with a correction factor applied. Equation 1 through 9 were used to calculate the intended properties.

Table 2. Formulation details and alkalinity levels of bentonite-based water-based drilling mud samples.

Additives	Unit	Concentration				Function
		Control	A	B	C	
Water	ml	350	350	350	350	Base fluid
Caustic potash (KOH)	g		40+	40+	40+	Alkalinity control
pH (obtained from addition of KOH)		~7.5	8	10	12	
Bentonite	g	21.5	21.5	21.5	21.5	Key clay component (Viscosifier)

Plastic Viscosity (PV): $\mu_p = \theta_{600} - \theta_{300}$ (cp) (1)

Apparent Viscosity (AV): $\mu_a = \frac{1}{2}\theta_{600}$ (cp) (2)

Bingham Yield point (YP): $\gamma_b = \theta_{300} - \mu_p$ (lb/100ft^2) (3)

Low-stress Yield point: LSYP = $3\theta_3 - \theta_6$ (lb/100ft^2) (4)

Shear stress: $\tau = 1.06 \times \theta$ (lb/100 ft^2) (5)

Dynamic viscosity: $\mu = \frac{shear\ stress}{shear\ rate} = \frac{\tau}{\dot{\gamma}}$ (Pa.s) (6)

Lubricity coefficient = $\frac{Meter\ reading\ \times Correction\ \ Factor}{100\ Pounds}$ (7)

$$\text{Correction Factor (CF)} = \frac{Standard\ Meter\ reading\ for\ Deionized\ Water}{Meter\ Reading\ Obtained\ in\ Deionized\ Water\ Calibration} \quad (8)$$

$$\text{CF} = \frac{34}{Meter\ \ Reading\ \ (32\ to\ 36)} \quad (9)$$

where μ_p is the plastic viscosity (PV) in centipoise (cp), μ_a denotes apparent viscosity (AV) in cp, y_b represent Bingham yield point (YP) in lb/100ft^2, LSYP refers to low stress yield point in lb/100ft^2, τ is the shear stress in lb/100ft^2, μ is dynamic viscosity in Pa.s, and CF is correction factor. The meter reading for fresh water calibration from the equipment was 33.5, which gives a correction factor of 1.015.

All mud formulations corresponding to the investigated pH levels (7.5, 8, 10, and 12) were prepared and evaluated under identical laboratory conditions following the procedures specified in API RP 13B-1. Each formulation was tested once after thorough mixing and stabilization, and the reported values therefore represent single experimental measurements rather than averaged data from repeated trials.

The objective of the study was to examine the systematic response of bentonite-based drilling mud properties to progressively increasing alkalinity, rather than to quantify experimental variability. Because the same preparation protocol, material composition, and testing conditions were maintained for all samples, the resulting dataset enables a consistent comparison of trends across the investigated pH range.

Rheological modelling of the fluid samples

Rheological modelling was performed to quantify the influence of alkalinity on the flow behavior of the bentonite-based drilling muds and to identify the constitutive model that best represents each fluid system. Experimental shear stress–shear rate data for the control (pH = 7.5) and alkaline samples of A (pH = 8), B (pH = 10), and C (pH =12) were fitted to the Bingham plastic (Equation 10), Power-law (Equation 11), and Herschel–Bulkley (Equation 12) models, which are widely applied to drilling fluids due to their ability to represent yield stress and shear-thinning behavior (Caenn et al., 2011; Rafieefar et al., 2021; Aliu et al., 2025a). Model parameters were obtained through nonlinear regression using Microsoft Excel Solver by minimizing the difference between experimental and predicted shear stress values. The adequacy of each model was evaluated using the coefficient of determination (R^2) (Equation 13), sum of squared residuals (SSR) (Equation 14), and root mean square error (RMSE) (Equation 15). High R^2 values combined with low SSR and RMSE were taken as indicators of strong model performance and reliable representation of fluid behavior. This approach enabled direct comparison of how increasing alkalinity alters the rheological structure and predictability of bentonite-based muds across different modelling frameworks.

$$\tau = \tau_0 + \mu_p \dot{\gamma} \quad (10)$$

$$\tau = K\dot{\gamma}^n \quad (11)$$

$$\tau = \tau_0 + K\dot{\gamma}^n \quad (12)$$

$$r^2 = 1 - \frac{\sum(O_i - P_i)^2}{\sum(O_i - \bar{O})^2} \quad (13)$$

$$SSE = \sum_{i=1}^{n}(P_i - O_i)^2 \quad (14)$$

$$RMSE = \sqrt{\sum_{i=1}^{n}\frac{(P_i - O_i)^2}{n}} \quad (15)$$

where γ represents shear rate (s^{-1}), K represents consistency coefficient ($Pa.s^n$), n in eqns. 11 and 12 is the flow behavior index (dimensionless).

For model evaluation, O_i and P_i denote the experimental and predicted values of the response variable, respectively, while n in eqns. 13–15 represents the total number of observations. The index i corresponds to individual data points.

The experimental shear stress–shear rate data fitted to commonly use rheological models using nonlinear least-squares regression was to further interpret the rheological behavior of the drilling muds. The fitting procedure was performed iteratively to minimize the sum of squared residuals between the measured and predicted shear stress values (Equation 14). Convergence of the regression solution was considered achieved when successive iterations produced negligible changes in parameter estimates and the residual error reached a stable minimum.

RESULT AND DISCUSSION

Table 3 presents the viscometer readings of the mud samples while Table 4 presents the PV, AV, YP, and LSYP of the samples calculated using Equation 1 – 4, respectively. It also included the 10 min gel strength of the samples. All the experiments were carried out at room temperature of about 29 °C.

The very low viscometer readings (Table 3) observed for the bentonite solutions across the applied shear rates can be attributed to the combined effects of pH conditions, quality and concentration of the bentoite, and the absence of rheology-modifying additives (Gamal et al., 2019; Huang et al., 2016; Safi et al., 2016; Ouaer, 2024). Bentonite suspensions develop their viscosity primarily from platelet-to-platelet interactions, which are strongly influenced by surface charge distribution (Huang et al., 2016). At the tested pH values, the electrostatic repulsion between clay platelets likely prevented effective edge-to-face association, thereby limiting gel structure development. In addition, no viscosifiers or rheology control additives such as polymers or fluid-loss agents were incorporated to enhance network formation and strengthen the suspension. As a result, the bentonite solutions lacked the structural integrity required to resist shear, leading to weak gel strength and extremely low apparent viscosity values under the measured shear rates. This indicates that both pH imbalance and the absence of viscosity enhancers played a key role in suppressing rheological buildup.

Note that some of the readings obtained at 3 rpm (Table 3) are greater than those obtained at higher shear rates (6 rpm – 300 rpm). Bentonite-based fluids are thixotropic, meaning their apparent viscosity decreases as the rate of shear increases (Agwu et al., 2021; Mahmud et al., 2026; Mahdi, 2025). At a very low shear rate (3 rpm), the structure of hydrated bentonite platelets remains relatively intact, creating a strong internal resistance to flow. This results in a high dial reading, which reflects the gel strength and yield stress of the mud. However, as the viscometer speed increases to 30 or 60 rpm, the applied shear disrupts the platelet network, aligns the particles, and reduces interparticle resistance. Consequently, the fluid flows more easily, and the dial readings drop. This characteristic is vital in drilling operations as high low-shear readings ensure effective cuttings suspension when circulation stops, while reduced high-shear viscosity lowers pump pressures and energy demands during active circulation. Thus, a higher 3 rpm reading than 30 or 60 rpm is possible, and it highlights the crucial balance bentonite muds maintain between suspension capability and ease of flow.

Table 3. Viscometer dial readings of bentonite-based water-based drilling muds at varying pH levels measured at 29 °C.

Dial speed (rpm)	Control (7.5)	8	10	12
600	13.00	10.50	9.00	6.00
300	8.00	6.50	5.50	3.50
200	6.00	5.50	5.00	3.00
100	4.00	4.00	3.00	2.00
60	3.00	3.00	2.00	2.00
30	2.00	2.00	2.00	2.00
6	1.50	1.50	1.50	1.50
3 (10 sec)	2.00	2.00	2.00	2.00
3 (10 min)	3.00	3.00	3.00	4.00

Table 4. Derived rheological parameters (PV, AV, YP, GS, and LSYP) of bentonite-based water-based drilling muds as a function of pH at 29 °C.

Rheological properties	Control (7.5)	8	10	12
PV	5.00	4.00	3.50	2.50
AV	6.50	5.25	4.50	3.00
YP	3.00	2.50	2.00	1.00
GS	3.00	3.00	3.00	4.00
LSYP	4.50	4.50	4.50	4.50

Flow behavior and shear - dependent response under varying alkalinity

(Table 5) and Figure 1 presents the shear stress–shear rate relationships for bentonite-based drilling muds formulated at different pH levels and tested at 29 °C. Across all pH conditions, the muds exhibit non-Newtonian, shear-thinning behavior, characterized by a nonlinear increase in shear stress with increasing shear rate. This response is consistent with the expected behavior of clay-based suspensions and confirms the suitability of bentonite as the primary viscosifying agent (Darley & Gray, 1988; Caenn et al., 2011).

However, increasing alkalinity produces a systematic reduction in shear stress at equivalent shear rates. At near-neutral to mildly alkaline conditions (pH 7.5–8), the mud displays higher resistance to flow, indicating stronger interparticle attraction and partial edge–face associations among bentonite platelets. As pH increases to 10 and 12, the shear stress curves shift downward, reflecting progressive weakening of the internal mud structure. This behavior can be attributed to enhanced electrostatic repulsion arising from increased negative surface charge density on bentonite particles under alkaline conditions (Huang et al., 2016; Rafieefar et al., 2021). The expansion of the electrical double layer promotes platelet dispersion, reduces particle–particle contacts, and weakens the three-dimensional clay network responsible for resistance to flow. Consequently, the mud becomes increasingly susceptible to deformation under shear.

The pronounced divergence between low- and high-pH curves at low shear rates suggests that alkalinity exerts a stronger influence on structure-building mechanisms than on high-shear flow, where hydrodynamic forces dominate. This observation has important operational implications, particularly for hole cleaning and suspension performance during low -circulation or static conditions.

Table 5. Measured shear stress–shear rate data for bentonite-based drilling muds at different alkalinity levels for dynamic viscosity evaluation.

Shear rate (γ), s $^{-1}$	Shear-stress (τ), lb/ft^2			
	Control (7.5)	8	10	12
1022	13.78	11.13	9.54	6.36
511	8.48	6.89	5.83	3.71
341	6.36	5.83	5.30	3.18
170	4.24	4.24	3.18	2.12
10.2	1.59	1.59	1.59	1.59
5.11	2.12	2.12	2.12	2.12

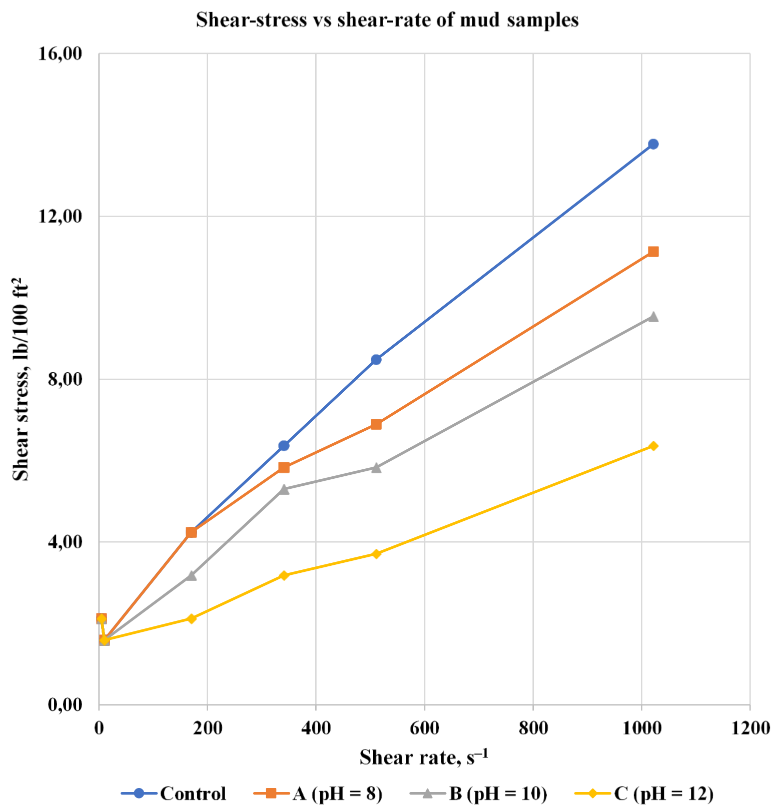

Figure 1. Shear stress–shear rate response of bentonite-based water-based drilling muds at varying pH levels measured at 29°C. Increasing pH reduces shear stress at comparable shear rates, indicating weakened interparticle interactions and reduced structural integrity of the bentonite network under alkaline conditions.

Influence of alkalinity on rheological parameters

The effects of pH on plastic viscosity (PV), yield point (YP), and gel strength are summarized in Table 3 and Figures 2–4. Increasing alkalinity results in a marked and consistent decline in both PV and YP. Relative to the control mud (pH 7.5), PV decreases by approximately 50% at pH 10 and by over 65% at pH 12, while YP exhibits an even more pronounced reduction.

The decline in PV reflects a reduction in internal friction arising from enhanced particle dispersion and decreased effective solids interaction. Under high pH conditions, bentonite platelets experience stronger mutual repulsion, limiting floc formation and lowering resistance to laminar flow (Gamal et al., 2019). This effect, while beneficial for reducing pump pressure losses, may compromise the mud's ability to transport cuttings efficiently at low annular velocities. Yield point, which is closely associated with interparticle attractive forces and network strength, is particularly sensitive to alkalinity. The sharp decrease in YP with increasing pH indicates disruption of the weak gel structure responsible for initiating flow. This trend is consistent with earlier studies reporting that excessive alkalinity destabilizes clay networks by suppressing edge–face interactions (Rafieefar et al., 2021; Mohamed et al., 2021).

Gel strength measurements (10-s and 10-min) show comparatively modest variation with pH (Table 3), suggesting that while the initial structural framework weakens, some degree of time-dependent particle association remains. This residual gel structure may be attributed to mechanical entanglement and short-range van der Waals forces that persist even under strongly alkaline conditions.

Figure 3 further clarifies the relative evolution of yield stress and viscous resistance by presenting the YP/PV ratio as a function of pH. This ratio, often used as an indicator of cuttings-carrying capacity relative to flow resistance, shows a slight increase at pH 8, suggesting a short-lived enhancement in structural efficiency at mild alkalinity. Beyond this point, the ratio declines sharply and collapses at pH 12, reflecting a disproportionately rapid loss of yield point compared to the reduction in plastic viscosity.

This behavior is consistent with progressive disruption of the bentonite particle network under strongly alkaline conditions, where electrostatic repulsion suppresses interparticle bonding more severely than it reduces viscous drag. The observed trend supports the view that excessive alkalinity undermines the balance between suspension capacity and pumpability, as the collapse of yield stress outpaces the decrease in flow resistance at very high pH (Ouaer 2024).

Overall, the rheological data demonstrate that while alkalinity improves mud fluidity, excessive pH levels significantly undermine the structural integrity required for effective hole cleaning and suspension, highlighting the need for controlled alkalinity rather than indiscriminate pH elevation. The YP/PV ratio (Figure 3) slightly increases at pH 8 then collapses at pH 12, consistent with the YP collapse outpacing PV drop at very high pH (Ouaer, 2024). The findings of Gamal et al. (2019), Rafieefar (2021), Huang (2016), and Ouaer (2024) all supported the experimental trend and the interpretation in this study that high alkalinity weakens bentonite's rheological network.

Alkalinity - driven changes in filtration and filter cake characteristics

API filtration results and corresponding filter cake thicknesses are presented in Figures 5 and 6. The data reveal a strong dependence of fluid loss behavior on pH, with filtration volume increasing progressively as alkalinity rises. The control mud exhibits the lowest fluid loss, while the pH 12 system records more than a threefold increase. This deterioration in filtration performance can be directly linked to the rheological and microstructural changes induced by alkalinity. At lower pH, partially flocculated bentonite particles form a relatively compact, low-permeability filter cake that effectively restricts filtrate invasion. As pH increases, enhanced particle dispersion inhibits the formation of a dense, interlocking cake structure, resulting in thicker yet more permeable filter cakes (Caenn et al., 2011; Oliveira et al., 2018).

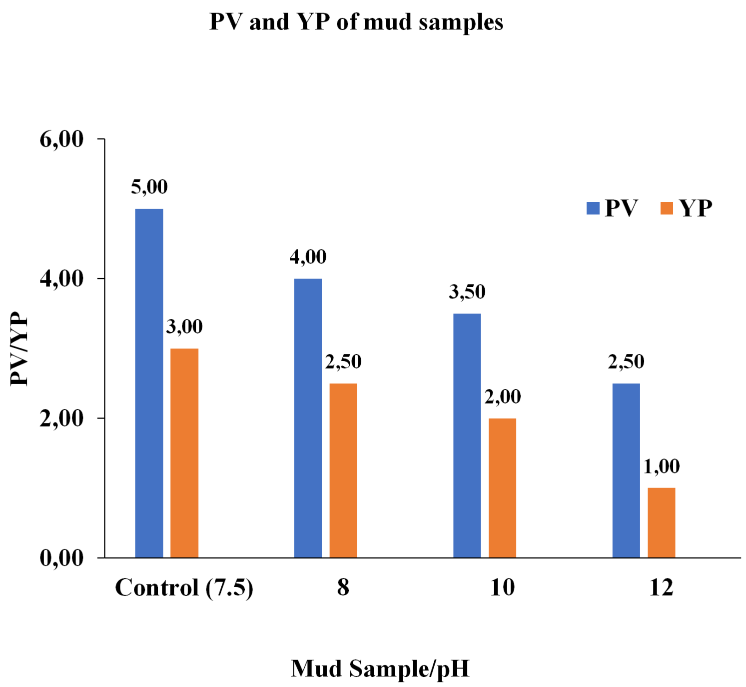

Figure 2. Variation of plastic viscosity and yield point of bentonite-based water-based drilling muds with increasing pH at 29 °C. Both PV and YP decrease with increasing pH, reflecting diminished solids interaction and reduced resistance to flow in highly alkaline environments.

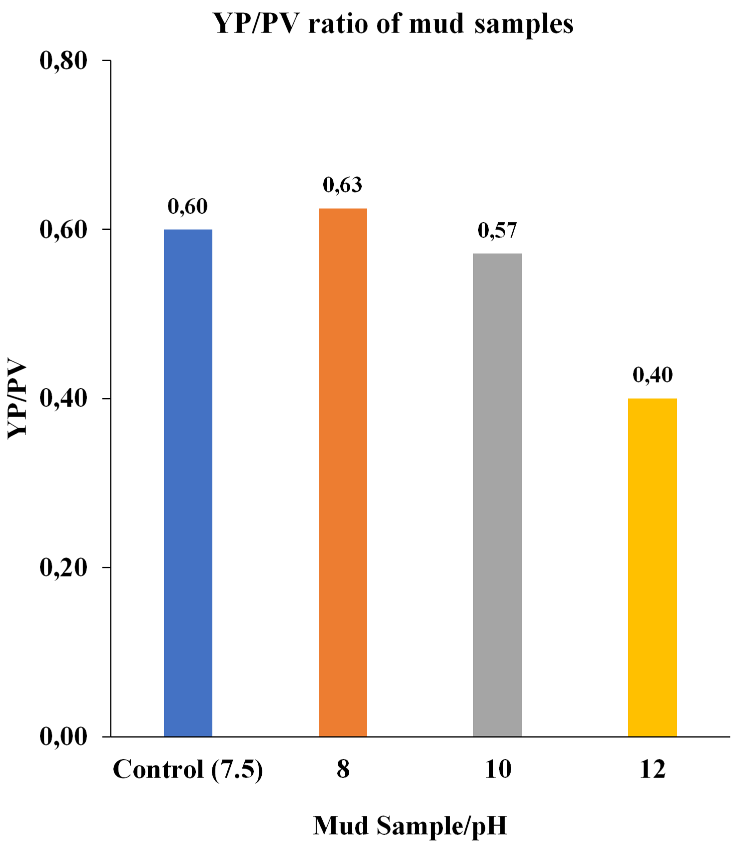

Figure 3. Effect of alkalinity on the yield point–plastic viscosity (YP/PV) ratio of bentonite-based water-based drilling muds. The declining YP/PV ratio with pH suggests reduced carrying capacity and poorer hole-cleaning efficiency as alkalinity increases.

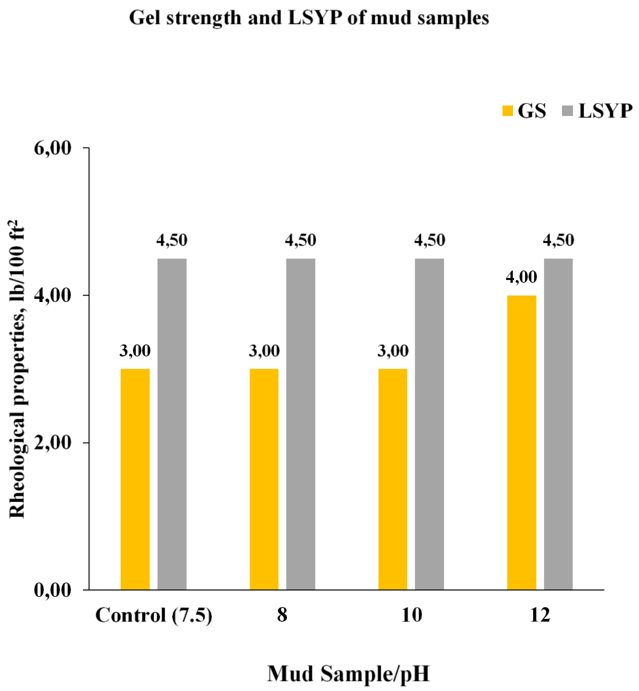

Figure 4. Gel strength development of bentonite-based water-based drilling muds at different pH levels. Gel strength development weakens at higher pH, indicating reduced thixotropic structure and lower suspension capacity during static conditions.

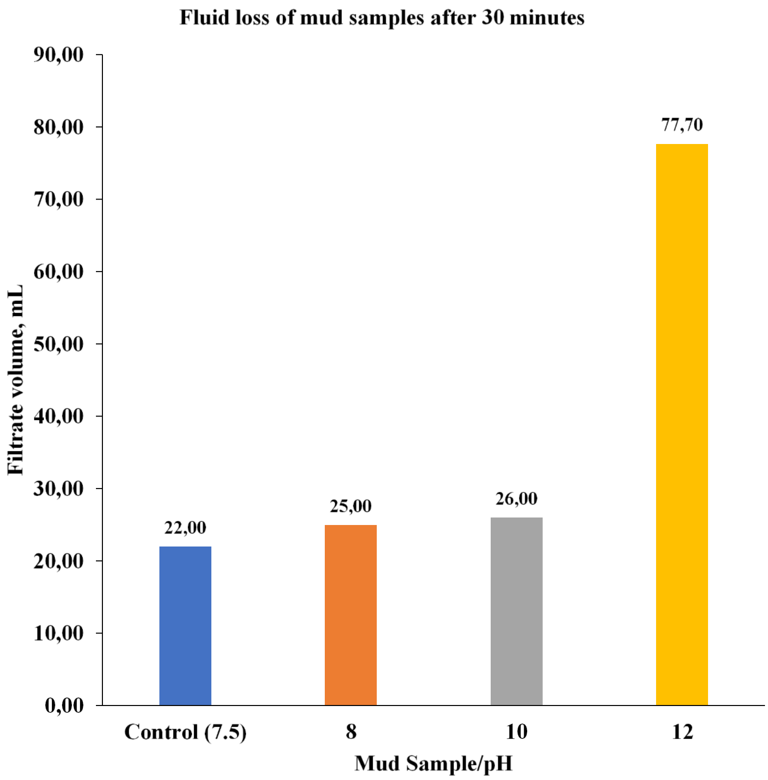

Figure 5. API filtrate volume of bentonite-based water-based drilling muds after 30 minutes as a function of pH. Filtrate volume increases with pH, highlighting the adverse effect of alkalinity on fluid loss control and filter cake sealing efficiency.

The increase in filter cake thickness observed at higher pH levels further suggests that dispersed particles are deposited inefficiently, creating loosely packed layers with poor sealing capacity. This phenomenon is particularly undesirable in field operations, as excessive filtrate invasion can destabilize the wellbore, damage formations, and increase the risk of differential sticking. Such invasion can alter near-wellbore saturation and pressure behavior, potentially accelerating water influx into hydrocarbon-bearing zones, as demonstrated through aquifer–reservoir interaction analyses (Aliu et al., 2025b). This effect is particularly critical in heavy hydrocarbon reservoirs, where water invasion and alkaline filtrates can significantly impair flow characteristics and hydrocarbon mobility (Akinsete et al., 2025).

These results underscore a critical trade-off, indicating that while alkalinity may improve flow properties, it simultaneously compromises filtration control in additive-free bentonite systems. This finding reinforces the importance of maintaining pH within an optimal window or supplementing alkalinity control with appropriate fluid-loss additives in practical drilling applications.

Effect of pH on lubricity behavior of bentonite-based mud

Lubricity coefficients measured at different pH levels are presented in Figure 7. Unlike rheological and filtration properties, lubricity exhibits a modest but consistent improvement with increasing alkalinity. While lower lubricity coefficients indicate better lubrication, the obtained values are slightly above the acceptable range of 0.15 – 0.40 for water-based muds (Fadairo et al., 2019; Fadairo et al., 2021). The lubricity coefficient decreases gradually from 0.49 at pH 7.5 to 0.43 at pH 12, indicating reduced frictional resistance at the metal – mud interface.

This improvement is primarily attributed to reduced bulk viscosity and yield stress at higher pH, which lowers resistance to sliding motion under boundary lubrication conditions (Gamal et al., 2019). Additionally, increased alkalinity may

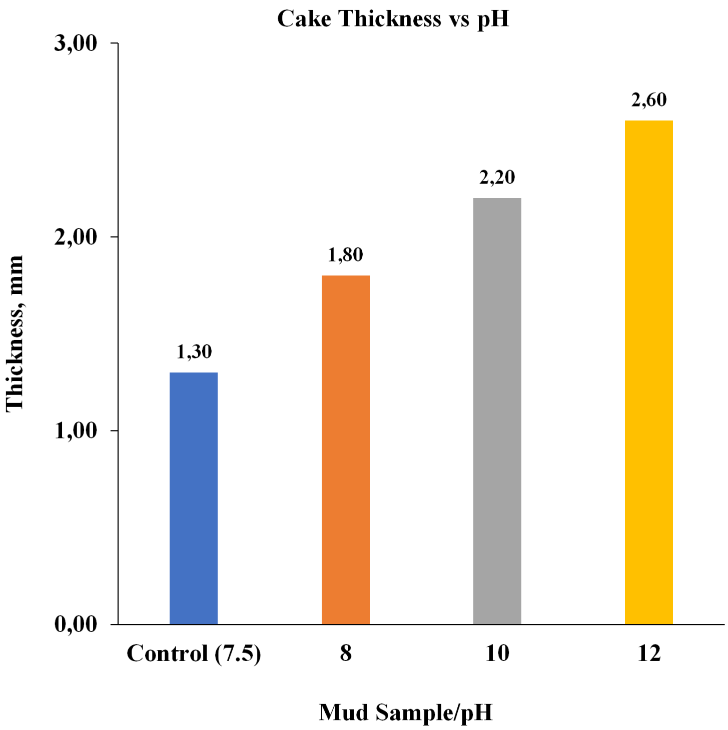

Figure 6. Influence of alkalinity on filter cake thickness of bentonite-based water-based drilling muds. Filter cake thickness increases slightly with pH, suggesting formation of a more porous and less compact cake under highly alkaline conditions.

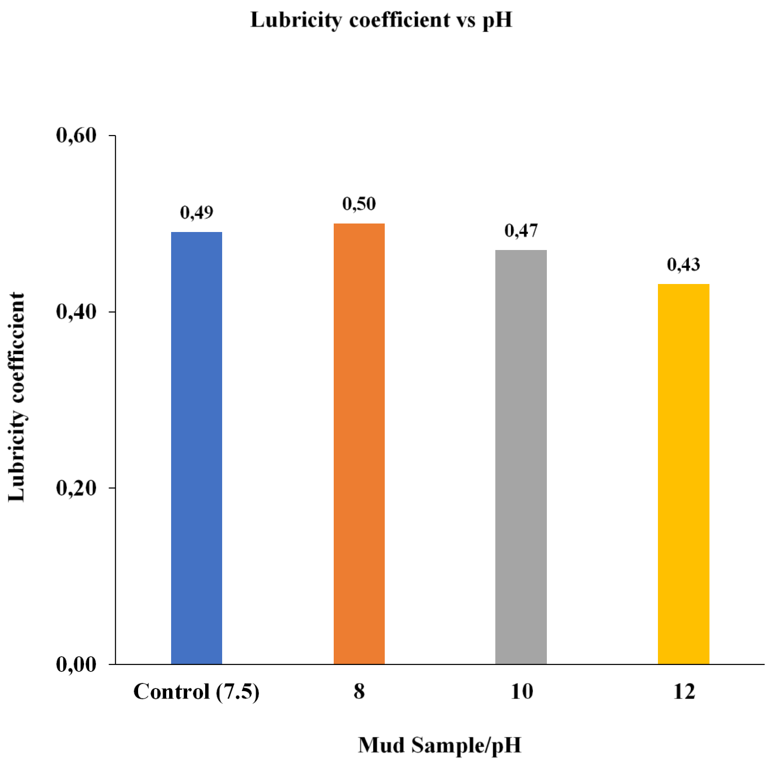

Figure 7. Variation of lubricity coefficient of bentonite-based water-based drilling muds with pH at 29 °C. Lubricity coefficient decreases with increasing pH, indicating improved lubricating performance, likely due to enhanced particle dispersion and reduced frictional resistance.

promote the formation of thinner, more uniform fluid films between contact surfaces, reducing asperity interactions (Samura et al., 2025).

However, the magnitude of lubricity enhancement remains limited compared to the pronounced deterioration observed in rheological and filtration properties. This suggests that alkalinity alone is insufficient to deliver substantial lubricity gains in bentonite-based WBM and that dedicated lubricating additives are necessary where torque and drag reduction is critical (Perumalsamy et al., 2021). Importantly, the results highlight a performance imbalance: the marginal lubricity benefits gained at high pH come at the expense of mud structure and fluid-loss control. This reinforces the need for holistic mud design strategies that balance friction reduction with wellbore stability and hydraulic performance.

Rheological models of fluid sample

- Rheological Model Performance and Goodness of Fit

  The rheological modelling results summarized in Table 6 show that all fluid samples exhibit non-Newtonian, shear-thinning behavior, as evidenced by flow behavior indices ($n < 1$) obtained from the Power-law and Herschel–Bulkley models. The control mud displayed excellent agreement with the Bingham plastic model ($R^2 = 0.9937$), reflecting a well-developed yield structure and relatively linear stress–rate relationship typical of stable bentonite dispersions (Darley & Gray, 1988; Huang et al., 2016). Sample A (pH 8) was best represented by the Herschel–Bulkley model, which yielded the highest R^2 and lowest error metrics, indicating that mild alkalinity preserves yield stress while introducing controlled nonlinearity in flow behavior. As alkalinity increased to pH 10 (sample B), model performance declined across all constitutive equations, with higher SSR and RMSE values suggesting increasing deviation between experimental data and model predictions. This trend became more pronounced for sample C (pH 12), which exhibited the poorest fits, particularly for the Power-law and Herschel–Bulkley models. The deterioration in model fidelity at high pH indicates significant disruption of the bentonite network, resulting in unstable rheological behavior that cannot be adequately captured by conventional models, consistent with earlier observations on excessive clay dispersion under strongly alkaline conditions (Gamal et al., 2019; Ouaer 2024). Although the Bingham model provides a useful approximation for drilling fluids, bentonite suspensions often display non-linear shear-thinning behavior, particularly when particle interactions change with alkalinity. Consequently, minor irregularities in fitted parameters may occur even when regression convergence is fully achieved. The resulting model parameters presented in Table 6 therefore represent the best-fit solutions obtained from the regression analysis.

- Effect of Alkalinity on Rheological Model Parameters

  Analysis of model parameters reveals a systematic weakening of bentonite structure with increasing pH. In the Bingham plastic model, the control sample exhibited the highest yield stress, reflecting strong interparticle bonding and resistance to flow initiation. A marked reduction in yield stress was observed for sample A, followed by irregular trends at higher pH, indicating progressive loss of structural rigidity due to enhanced electrostatic repulsion between negatively charged clay platelets (Huang et al., 2016). Plastic viscosity similarly decreased with alkalinity, confirming reduced interparticle friction and hydrodynamic resistance. In the Power-law model, all samples retained shear-thinning behavior; however, sample A exhibited a flow behavior index closest to unity, suggesting a more stable and predictable flow response. Samples B and C showed lower n and K values, reflecting increased shear sensitivity and diminished consistency. The Herschel–Bulkley model further highlights that mild alkalinity optimizes the

Table 6. Rheological model parameters of the drilling fluids.

		Control (7.5)	8	10	12
BINGHAM PLASTIC	τ_0	13.4575	4.5729	8.7429	8.5371
	μ_p	0.0565	0.0217	0.0296	0.0317
	SSR	5787.4153	390.6806	1590.1970	2139.4492
	RMSE	31.0575	8.0693	16.2798	18.8832
	R^2	0.9937	0.9812	0.9814	0.9759
POWER LAW	K	2.8753	0.5615	2.1772	1.9885
	n	0.4502	0.5477	0.4016	0.4229
	SSR	5951.2772	384.4936	1607.7219	2197.9985
	RMSE	31.4941	8.0051	16.3693	19.1398
	R^2	0.9445	0.9775	0.9185	0.8120
HERSCHEL-BULKLEY	τ_0	3.4464	4.1243	5.5186	3.5262
	K	1.7585	0.0428	0.3913	0.8007
	n	0.5153	0.9025	0.6330	0.5439
	SSR	5947.7492	389.8653	1610.1538	2194.4521
	RMSE	31.4848	8.0609	16.3817	19.1244
	R^2	0.9616	0.9895	0.9735	0.8667

balance between yield stress and shear thinning, while excessive alkalinity degrades both parameters. These trends demonstrate that increasing pH initially promotes bentonite dispersion beneficial to flow control but ultimately leads to structural breakdown at extreme alkalinity, consistent with rheological and physicochemical behavior reported in prior studies (Caenn et al., 2011; Rafieefar et al., 2021).

- Implications of Rheological Modelling for Drilling Performance

From an operational standpoint, the modelling results indicate that moderate alkalinity produces the most desirable rheological behavior for drilling applications. Sample A, characterized by high model predictability and balanced yield –shear-thinning response, represents a condition where cuttings suspension, hole cleaning, and hydraulic efficiency can be simultaneously optimized. In contrast, the poor model performance and reduced structural parameters observed for sample C suggest that extreme alkalinity compromises mud stability, increasing the risk of inefficient cuttings transport and erratic pressure losses. These findings align with field practices that recommend maintaining water-based muds within controlled alkaline ranges to avoid clay degradation and excessive thinning (Baker Hughes, 2006; Gamal et al., 2019; Ouaer, 2024; Mahdi, 2025). The modelling outcomes therefore reinforce the importance of alkalinity control as a primary design parameter in bentonite-based drilling fluids, rather than relying on excessive chemical adjustment to compensate for degraded rheological structure.

- Linking Rheological Modelling with Filtration and Lubricity Behavior

The rheological modelling outcomes provide a mechanistic basis for the filtration and lubricity trends observed in this study. The well-defined yield stress and higher consistency coefficients associated with the control and mildly alkaline sample A correspond to reduced API fluid loss, as a stronger bentonite network promotes formation of low-permeability filter cakes

(Darley & Gray, 1988; Caenn et al., 2011). Conversely, the structural breakdown indicated by declining model parameters at higher pH explains the increase in fluid loss observed for samples B and C, where excessive clay dispersion weakens filter cake integrity. Similarly, the reduced yield stress and viscosity at elevated alkalinity contribute to improved lubricity by lowering interfacial friction and shear resistance, consistent with the observed decrease in lubricity coefficient (Fadairo et al., 2019; Fadairo et al., 2021). However, the modelling results show that this lubricity improvement occurs at the expense of rheological stability and filtration control. Together, these findings demonstrate that rheological modelling serves as a unifying framework linking alkalinity-driven changes in flow behavior, filtration performance, and lubricity, highlighting the need for balanced pH optimization rather than extreme alkalization in bentonite-based water-based drilling muds.

- Environmental Implications of the Study

The findings highlight that pH control in water-based drilling muds carries significant environmental consequences. At elevated pH (10–12), the mud became less viscous and exhibited excessive fluid loss, which risks greater filtrate invasion into surrounding formations. Such invasion can mobilize formation fines, increase reservoir damage, and lead to contamination of aquifers. The thickened filter cakes observed at high pH also point to higher solid disposal burdens, complicating waste handling and treatment at the surface. Although higher alkalinity marginally improved lubricity, the accompanying loss of rheological integrity suggests increased circulation volumes and additive consumption would be required to maintain hole stability. This translates into greater chemical usage, higher waste streams, and a larger environmental footprint. By contrast, muds maintained near-neutral pH (7.5–8) in this study balanced lubricity, filtration control, and rheology more sustainably. It is important to note that the high fluid loss at pH 10 was due to lack of viscosifier and fluid loss control additives in the formulated samples. The presence of these additives would keep the pH at the practical Field range (between 9.5–10.5). Overall, the study underscores the need for tight pH management in WBM formulation. Avoiding excessively alkaline systems reduces risks of groundwater contamination, minimizes drilling waste, and ensures safer, more environmentally responsible drilling operations.

CONCLUSION

This study presents a systematic, additive-free assessment of how alkalinity governs the rheological, filtration, lubricity, and flow modelling behavior of bentonite-based water-based drilling mud. By isolating pH as the sole variable, the work clarifies fundamental clay–fluid interactions that are often obscured in chemically complex mud formulations. Experimental measurements and rheological modelling consistently show that increasing alkalinity intensifies electrostatic repulsion between bentonite platelets, leading to progressive dispersion and weakening of the mud's internal structure. Rheological model parameters and goodness-of-fit metrics reveal that moderate alkalinity preserves predictable yield and shear-thinning behavior, whereas extreme alkalinity (pH ≈12) results in poor model fidelity, reduced yield stress, and unstable flow response. These structural changes directly explain the observed deterioration in filtration performance, as excessive dispersion weakens filter cake integrity and increases fluid loss. Although lubricity improves slightly at higher pH due to reduced viscosity and diminished yield resistance, the improvement is modest and occurs at the expense of rheological stability and filtration control. A key outcome of this work is the identification of a clear performance trade-off, showing that alkalinity-driven gains in lubricity are insufficient to compensate for the substantial loss of mud structure and fluid-loss resistance at high pH. From an operational standpoint, the findings support maintaining bentonite-based WBM within a moderate alkaline range that balances clay dispersion with structural stability. The mechanistic insights provided offer a rational basis for pH optimization and underscore that effective drilling fluid design requires controlled alkalinity rather than excessive alkalization. Future studies should examine thermal effects, dynamic aging, and additive-modified systems to extend these findings toward field-scale applications.

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DECLARATIONS

Author contribution

A.J. Alawode: Conceptualization, Methodology, Supervision. A.T. Adeleke: Investigation, Resources, Writing – original draft. H.O. Aliu: Formal Analysis, Writing – review & editing, Visualization. A.A. Muhammed: Writing – review & editing.

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Competing interest

None

The use of AI or AI-assisted technologies

None

GLOSSARY OF TERMS AND SYMBOLS

Terms & Symbols	Definition	Unit
μ_a	Apparent Viscosity (AV)	Centipoise (cp)
μ_p	Plastic Viscosity (PV)	cp
YP	Bingham yield point	$lb/100ft^2$
LSYP	Low stress yield point	$lb/100ft^2$
τ	Shear stress	$lb/100ft^2$
μ	Dynamic viscosity	Pa.s
γ	Shear rate	s^{-1}
CF	Correction factor	
O_i	Experimental values of the response variable	
P_i	Predicted values of the response variable	
R^2	Coefficient of determination	
SSE	Sum of squares error	
RMSE	Root mean square error	
K	Flow consistency index	$Pa.s^n$
n	Flow behaviour index	
CMC	Caboxymethyl cellulose	
PAC	Polyanionic cellulose	
PC60	product of the reaction of glycerol+tall oil fatty acid	
XG	Xanthan Gum	

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